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THE ELECTRICAL CONDUCTION OF THIN AIR FILMS

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THE ELECTRICAL CONDUCTION OF THIN AIR FILMS

by

ALBERT JAMES WALKER

and

JOHN THOMAS LYNCH

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I

PROFESSOR ANDERSON'S EXPERIMENTS.

A series of experiments on the conductivity of thin air films at pressures varying from atmospheric to 2 mm. of mercury were conducted under the direction of Prof. A. Anderson, and reported by him in the Philosophical Magazine for May, 1912, and for August, 1913. These experiments were conducted with very low potentials, the figures mentioned varying from 30 to 100 volts. The distance between the electrodes was as great as .005 cm. and the end areas of the electrodes varied from 1.15 sq. cm. to 7 sq. cm.

In his earlier article, Prof. Anderson thinks that currents pass "for voltages much lower than 30 volts, and for distances between the electrodes much greater than that of one wave length of sodium light." In fact, he says, a decided current passes for a difference of potential of 30 volts when the distance between the electrodes is as great as .005 cm. Nothing is said in the earlier article as to whether or not the air between the plates was dry and dust free.

The following is a brief summary of the results described in the second article.

Two brass electrodes with end areas of 1.15 sq. cm. were set in paraffin blocks so that an air film of uniform thickness of .002 cm. was included between them. These electrodes were incased in an earthed copper box which was nearly air tight. Dry and dust free air was passed through the box at intervals for several days. It is claimed that a current passed between these electroded when the applied voltage was "very small" and that this current increased with the applied voltage according to Ohms law up to about 80 volts, and much more rapidly for higher voltages. It is stated further that as the air pressure was decreased, the current decreased, finally disappearing at 2 mm. of mercury. When air was afterward admitted, the current again increased but did not follow the same curve, showing a decided lag.

Prof. Anderson, in this paper, does not state what he means by "very low voltages", nor does he give either the sensibility of his electrometer nor the magnitudes of the currents obtained, so it is impossible to tell what he means by "decided currents". The only quantitative results given are for a difference of potential of 100 volts. The magnitude of the current in

this case varied from 2.8×10^{-13} amperes at atmospheric pressure to 1.3×10^{-13} amperes at 8 mm. pressure.

It has hitherto been thought that for a given gas at a given pressure there is a certain potential difference below which no current can be made to pass through the gas gap, no matter how close together the electrodes be placed.(1) This potential for air at atmospheric pressure has been supposed to be about 250 volts.

It is true that some experiments by Earhart seemed to show that currents pass when much lower voltages are applied provided the electrodes are close enough together.(2) Earhart obtained a current for potentials as low as 38 volts when the electrodes were placed .00003 cm. apart. When the electrodes were as far apart as .0002 cm., one-tenth the minimum distance mentioned by Prof. Anderson, he found that it required 350 volts to cause a current to pass. Futhermore, this current was in the nature of a short circuit, and not a slow leakage as described by Prof. Anderson. Hence these results are in no way analogous to Prof. Anderson's results,

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(1) Townsend: Ionization of Gases by Collision - p. 80.

(2) Phil. Mag., 1901; p. 147.

the current obtained being of a much greater order of magnitude, and the electrodes being many times closer together.

It has later been shown by J. E. Almy (1) that the results of Earhart were wrongly interpreted, and that the current did not pass through the air under these conditions but that the potential difference between the electrodes pulled them together, causing actual contact. Mr. Almy showed that, when the electrodes were rigidly fastened, no current would pass for applied potentials less than 350 volts, even when the electrodes were so close together as one-half the wave length of sodium light (.00003 cm.). It must be stated, however, in justice to Prof. Anderson, that both Earhart and Almy were, in all probability, looking for a comparatively large current, and might easily have overlooked so small a one as 3×10^{-13} amperes.

In explanation of his results, Prof. Anderson offers the following theory.

"Everything, therefore, points to the formation of ions in the surfaces of the film of air in contact with the ends of the bars, which become available as carriers

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(1) Phil. Mag., Sept., 1908.

when the opposing surfaces are close enough. These ions can be removed by removing the air; and when the air is introduced again, they are again formed, but not instantaneously. This formation requires time. It is probable that such layers of ions exist at the surfaces of all bodies in contact with the air, and that they play a prominent part in coherer action and in all cases of the discharge of bodies by contact."

II

FIRST SET OF EXPERIMENTS.

The purpose of our work was to throw further light on the matter taken up by Prof. Anderson, first, by duplicating his experiments as far as possible, showing that his results were not due to unknown local factors, and second by noting the results of variations in the apparatus.

The practical difficulties involved in measuring a current as small as that found by Prof. Anderson were very great. An extremely sensitive electrometer had to be used, and it was a matter of considerable difficulty to eliminate all effects other than those sought.

In our first set of experiments,the electrodes consisted of brass bars with carefully planed ends of about 1.2 sq. cm. area. These were mounted on parrafin blocks (as were Prof. Anderson's) and were set at the desired distance apart by pressing them against a thin sheet of mica while the paraffin was soft, letting them set, and then removing the mica. These were incased in a bell-

jar, the electrodes being connected to platinum wires fused through the glass.(1) The bell-jar was connected with an aspirator, for varying the pressure. All air admitted to the jar was passed through sulphuric acid and phosphorus pent-oxide to remove the moisture, and through tightly packed glass wool to remove the dust particles. The phosphorus pent-oxide was spread over broken pummice stone, to present as large a surface as possible to the air. A bottle of phosphorus pent-Oxide thus arranged was also placed between the aspirator and the jar to prevent moisture from entering the jar from this source.

All electrometer connections were screened from induced currents by incasing them in glass tubes, wrapped with tin foil which was grounded. The wires were kept out of contact with the glass tubes by sulphur plugs. The switches, in the first apparatus, consisted merely of cups in paraffin blocks filled with mercury, connected or disconnected at will by a bent wire with an insulating handle. These switches were incased in wire cages.

Many difficulties immediately presented them selves with this apparatus. In the first place, the paraffin blocks would gradually shift, and it was therefore difficult to keep the electrodes at the desired distance apart, and to be sure that they were not touching.

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(1) See p 25; Fig. IV.

As the bell-jar had only one opening, in order to pass in dry air it was necessary to pump the air out and allow more to enter successively. This, of course, had to be done a large number of times, and even then it is doubtful whether there was not still some moist air in the jar. It was especially difficult to make sure of this point because of the fact that the jar had to be frequently opened to the moist air of the room to adjust the electrodes.

It was found that the sulphur plugs, with which the wires were separated from their incasing tubes, the paraffin switches, and the paraffin blocks on which the electrodes were set, all easily acquired charges which were very difficult to remove.. These charged the wires leading to the electrometer, giving rise to all sorts of erratic effects.

Furthermore, although the switch handles were of insulating material, and the switches were encased in grounded wire cages, a slight motion of the hand in the neighborhood of a switch would almost invariably cause a deflection of the electrometer needle.

The results of the experiments with this apparatus were, for the most part, too erratic to bear much weight, but at times things seemed to work fairly well and a few runs were made which checked each other in a very gener-

al sort of a way. These runs seemed to show the existence of such an effect as Prof. Anderson describes. There was apparently a current of the same general order of magnitude as that mentioned. There seemed to be some evidence that this current decreased with air pressure. Beyond this we could venture no conclusions.

This current may have been due to the causes assigned by Prof. Anderson, to the presence of moisture or dust in the air, to a surface leakage over the paraffin, or to some unknown outside causes. It could not very well have been due to induction, as this would have given a permanent deflection and not a steady leak.

III

SECOND SET OF EXPERIMENTS.

In our second set up several important changes were made. Instead of setting the electrodes in paraffin blocks, they were rested in a groove in an amber bar.(1) The advantages of this arrangement were: (1) the electrodes remained firmly in place when once set, relieving us from the necessity of constantly opening the container to the damp air of the room in order to adjust them; (2) they could easily be set at any desired distance apart; (3) the troublesome static charges in the paraffin supports were done away with; (4) amber insulation being far better than paraffin, the chance for current leakage other than across the gap was very greatly lessened.

The electrodes were enclosed, this time, in an earthed brass box. The lead wires were brought in through ambeer plugs, set air tight. Two air openings

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(1) See Fig. III; p 24.

were made in the box so that air ~~iar~~ could be passed through for any desired length of time. This did away with the troublesome pumping out and letting in of air, and enabled us to make sure that the air in the box was thoroughly dry and free from dust.

The wires enclosed in glass tubes with the troublesome sulphur plugs were removed, and all connections were made through brass rods, set with sealing wax in grounded brass tubes. This sealing wax did not seem to become charged as readily as the sulphur and could easily be heated with a bunsen burner to drive off what charge there was, and to free the surface from moisture. The old paraffin switches were replaced by a much more satisfactory device.(1) A brass cup was melted into the end of a stick of sealing wax. This cup was filled with mercury. This cup was connected to ground and the electrometer was grounded and disconnected from earth at will by lowering or raising the wire connected to two quadrants of the electrometer. This wire dipped into the mercury cup, and was raised and lowered by means of a string. The entire switch was encased in a cage of wire gause connected to earth. The inside of the brass cup, and the end of the wire which dipped into the mercury was amalgamated to prevent contact difference of potential. This switch

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(1) See Fig's I & II, pp 23 & 24.

worked much better than the one used in the first set up. The sealing wax did not easily become charged, and when it did so the charge was removed by heating with a bunsen burner. The fact that the switch could be operated at a distance made it possible to place the entire apparatus, except the telescope and scale, at a distance from the observer. The erratic deflections due to moving the body in the neighborhood of the ~~scale~~ switch were thus done away with.

The method used for determining the magnitude of the current was based on the fact that current equals the rate of change of quantity. In order to compute the magnitude of a current by this method, it was necessary to know the constant deflection for a known difference of potential between the quadrants and the capacity of the system. The capacity was determined by the ordinary method of mixtures. First, a standard cell was connected to the electrometer and the deflection noted. The cell was then disconnected and the charge divided between the electrometer system and a standard condenser and the deflection noted. The

capacity was then computed from the relation:

$$C/(C+C_s) = D_2/D_1$$

where C is the capacity of the electrometer system, C_s that of the standard condenser, D_1 the deflection without the condenser, D_2 the deflection with the condenser.(1)

The capacity of the electrometer system was so small that it could not be compared with an ordinary micro-farad condenser. A standard condenser was therefore made, whose capacity was easily computable from its dimensions. The condenser was constructed as follows:(2)

Two brass tubes, one smaller than the other, were cut of equal length. The larger tube was placed on sealing wax supports. The ends of the smaller tube was plugged with corks and a brass rod about a foot longer than the tubes was passed through the senter. This tube was supported inside of the bigger one by resting the ends of the orojecting rod on sealing wax supports. The tubes were adjusted by heating the wax supports slightly and shifting until the tubes were concentric. The outer tube was grounded and the inner one was connected to the apparatus as described above. The capacity of this con-

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(1) For data and detailed computation of sensibility, see p. 28 et seq.

(2) See Fig. V, p 25.

denser was 150 electrostatic units. The sensibility of the galvanometer was found to such that a change in deflection of 1 mm. per second would be obtained for a current of 2.6 x 10^{-13} amperes.(1)

Although a very great improvement over the first, this second apparatus fell far short of giving entire satisfaction. Static charges still bothered at times, and as the set up was not completed until warm weather, it was found to be almost impossible to eliminate leakage entirely. The entire apparatus was placed over an electric heater with a view to eliminating this leakage, but the heater was found to ~~[illegible]~~ cause such disturbances in the electrometer that the scheme had finally to be abandoned.

There were times, however, when the apparatus worked rather consistently and it was at these times that the observations referred to in the next section were taken.

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(1) See p.

IV

RESULTS AND GENERAL DISCUSSION.

As stated in the last section, even after all the precautions described had been taken, the electrometer still showed erratic behavior at times. On at least four occasions, however, the electrometer behaved consistently. The static charges were small, causing a permanent deflection of about 1 cm. on disconnecting one pair of quadrants from earth. There seems to be no reason why this initial deflection should interfere with the detection of a current, though, to be sure, it might interfere with the determination of the exact magnitude of that current, were such exact determination desired. On two of these occasions, the electrometer showed no leakage, even when the quadrants were so charged that the needle had a permanent deflection of 300 mm. The leakage, then, must have been very slight indeed where the charge was only such as such as to cause a deflection of a centimeter or two, as would have been the case when the electrometer first began to charge up due to the current passing across the air gap. On two other occasions there was considerable leakage when the quadrants were charged so high as to give a deflection of 300 mm, this leakage amounting to five or six centimeters per minute, but even on these occasions, the leakage was barely perceptable when the quadrants were charged so as to give a de-

flection of four or five centimeters. The following experiments were tried on each of the four occasions, with the same result in each case.

The electrodes were placed .003 cm. apart. One pair of quadrants of the electrometer was grounded and the other pair connected to one of the electrodes. One terminal of an 85 volt battery was connected to the other electrode, the other terminal of the battery being grounded. Dry air was passed through the box. At first a decided current passed, but after passing the dry and dust free air through the box for four or five hours, absolutely no current could be detected. When the pair of quadrants which was connected with the electrode was first disconnected from earth static charges would cause, as stated, a permanent deflection of about a centimeter. That this charge was really due to static charges on the supports was proven by the fact that it would be obtained regardless of whether the electrometer was connected to the electrode or not. After this initial deflection the needle would come to rest, and no further deflection could be observed even in so long a time as ten minutes, the pressure in the box being atmospheric.

Our sensibility was such that a current of $2.6x10^{-13}$ amp's should have caused a deflection of of 1 mm. per second,

that is, of six cm. per minute. A deflection of 1 cm. in ten minutes would have been easily observable, hence it seems certain that no current greater than 5 x 10^{-15} passed through the air gap.

As stated above, Prof. Anderson, in his second paper, speaks of"decided currents" and "low voltages" and since he makes no mention of the sensibility of his electrometer, it is impossible to tell what he means by these indefinite terms. That the "low voltages" means voltages much lower than eighty is certain from the fact that he says that the current increases according to Ohm's law up to 80 volts applied potential. The only figures mentioned by him for currents passing at atmospheric pressure are 3.8 x 10^{-13} amperes for an applied potential of 100 volts when the electrodes are .002 cm. apart and their end areas 1.16 sq. cm. In our experiments, the applied potential was 85 volts, the distance between the electrodes .003 cm. and the end areas of the electrodes 1.2 sq. cm. Our valtage was therefore slightly smaller than Prof. Anderson's largest, and our air gap slightly thicker than his thinnest, but on the other hand, the end areas of our electrodes were slightly greater than his. In all respects

we were far within the limits within which Prof. Anderson obtained "decided currents". Since, as pointed out, we should have been able to observe a current 100 times smaller than the one mentioned by him, it seems reasonable to suppose that had there been any such effect as he describes, that we should have been able to detect it.

Before discussing the probable reasons for this discrepancy between our results and those of Prof. Anderson, we should like to point out the following facts:

Our insulation at all essential points was amber, the best of the common insulators, while that of Prof. Anderson was paraffin. Prof. Anderson passed dry and dust free air through his box "at intervals". Now we found that a decided current passed when purified air had been passed through for only an hour, but that this current disappeared entirely when the dry air had been passed through for four or five hours. Our air was passed through sulphuric acid, phosphorus pent-oxide and glass wool in succession. Prof. Anderson does not mention what drying agents he used.

We think, therefore, that the effect described by Prof. Anderson might have been due either to surface leakage on the paraffin or to the presence of moisture and dust in the air, and not to the formation of a layer of

ions at the surface of the metal as he supposed.

While, therefore, we admit that our results are far from conclusive, the best interpretation that we can make of them raises a doubt in our minds as to the correctness of Prof. Anderson's conclusions. We feel that the matter at least warrants further investigation.

It is our sincere regret that time limitations have not allowed us to go more deeply into the matter, so that we might have obtained results that would have enabled us to finally confirm or deny these conclusions. Before stating finally that these conclusions are at fault, the following changes should be made in the apparatus:

The electrodes should be set at least as close as .002 cm. The size of these electrodes might be increased to advantage. The applied potential should be made at least 100 volts.

If, as we believe would be the case, no current should be observed under these conditions when the air between the electrodes is thoroughly dry and dust free and the insulations are made as nearly perfect as possible, a little unpurified air should be admitted to the box. Our results show that a current would be obtained under these conditions. This current should then be carefully studied for different air pressures in the box. If the results thus obtained agreed in form with those of Prof. Anderson, it would seem reasonably certain that the ef-

fects described by Prof. Anderson were due to the presence of small amounts of dust or moisture in the air.

If this was the case the results of his experiments can easily be explained on the basis of mechanical convection. A particle in contact with the positive pole would become charged positively. It would then be repelled by the positive pole and attracted by the negative pole. On reaching the negative pole, it would give up its charge, become charged negatively and would return to the positive pole with its negative charge. This process would be repeated indefinitely. Hence positive electricity would be conveyed across the air gap from the positive to the negative electrode and negative electricity would be conveyed from the negative to the positive electrode. In other words, a current would be passing across the air gap. That an effect of this sort should exist except in cases where the air film is thin, could hardly be expected. If the air gap is wide, the repellent action of the positive electrode on a positively charged particle might not be sufficient to carry it within reach of the attracting force of the negative electrode.

It would be expected that a current carried as described would decrease with air pressure. When the amount of air in the film is relatively small, the number of particles would be small, and hence there would not be so many available carriers. The fact that when air was afterwards admitted the

current did not immediately increase might also be very easily explained on the basis of this theory. On admitting more air to the box , a turbulent state of motion was set up. That is, the particles suspended in the air possessed kinetic energy. Now if this kinetic energy were sufficient, the faint attractive and repellent force of the electrodes could not be expected to divert the particles from their course. Hence no carriers would be available and no current would pass. The objection might here be raised that the air in the box must have also been turbulent while pumping out. This is of course true, but whether the disturbance was greatest when observations were being taken while the pressure was being increased or when they were being taken while the air was being let into the box, would depend entirely on the arrangement of the apparatus and the method of conducting the experiments.

It would be very interesting indeed to test out the various points mentioned in the above suggested explanation of Prof. Anderson's results. This could be done without great difficulty, in ways which readily suggest themselves.

V

DIAGRAMS AND COMPUTATIONS.

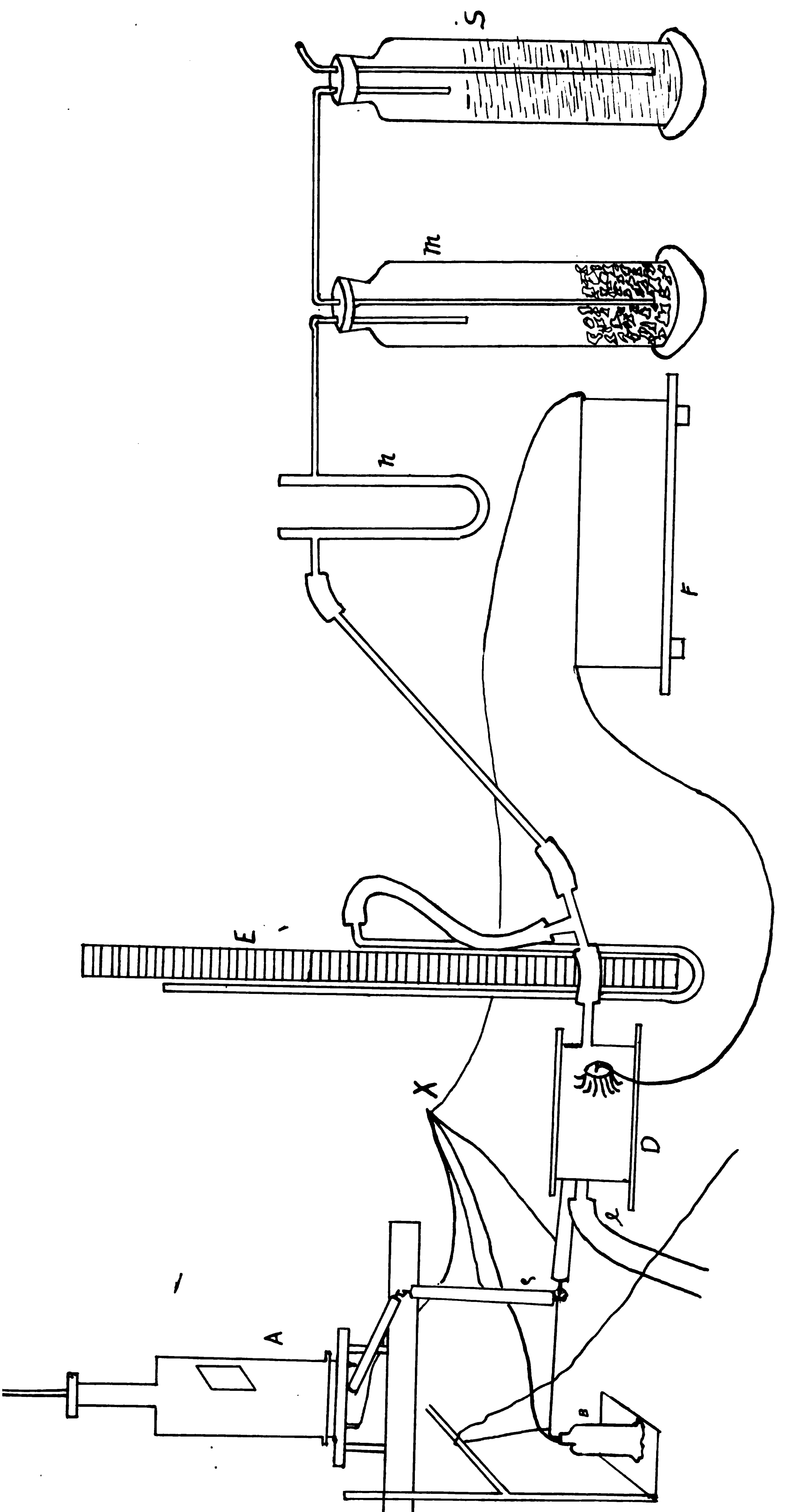


Fig I

Fig II

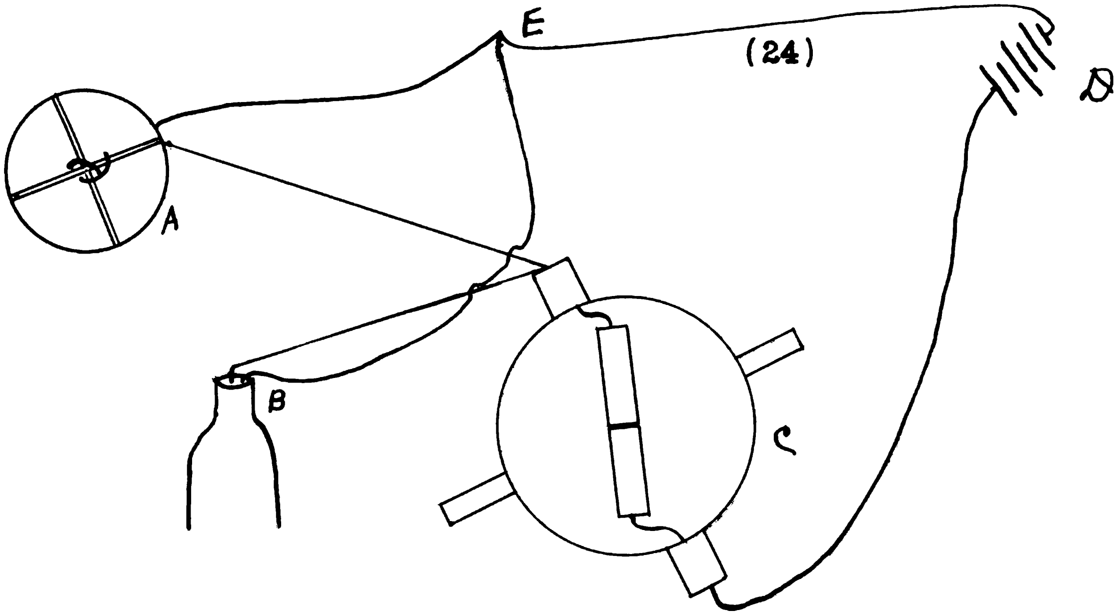
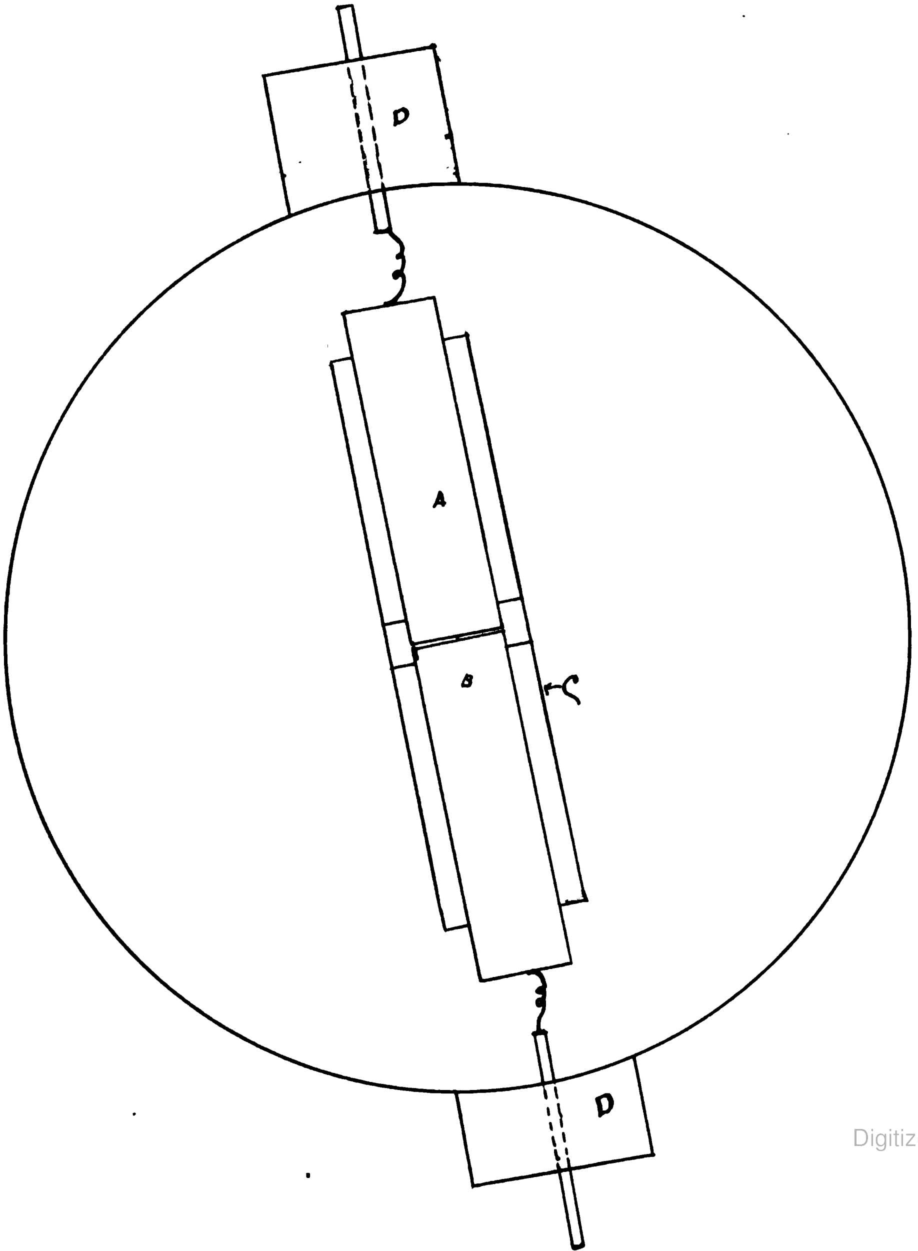


Fig III



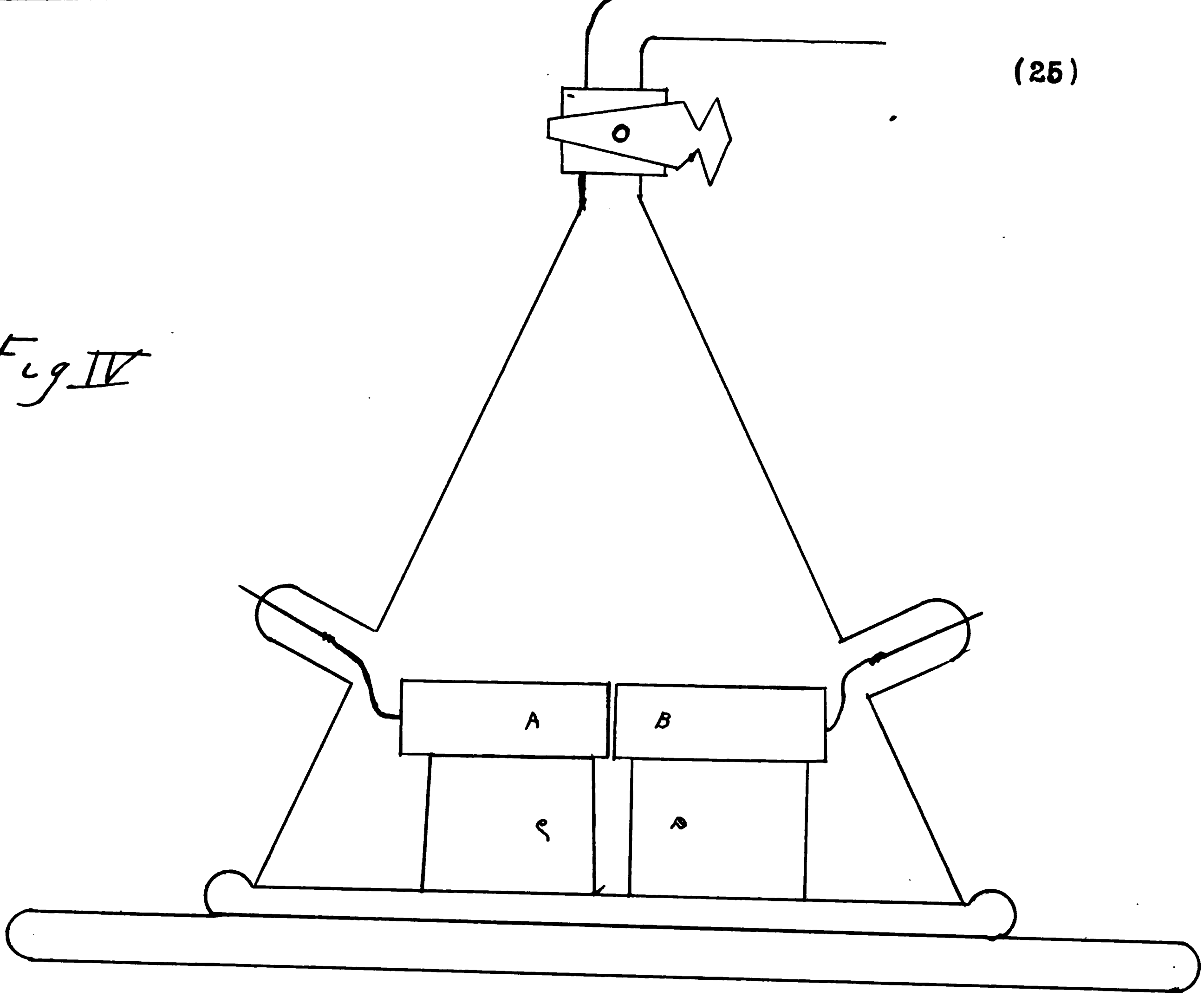


Fig IV

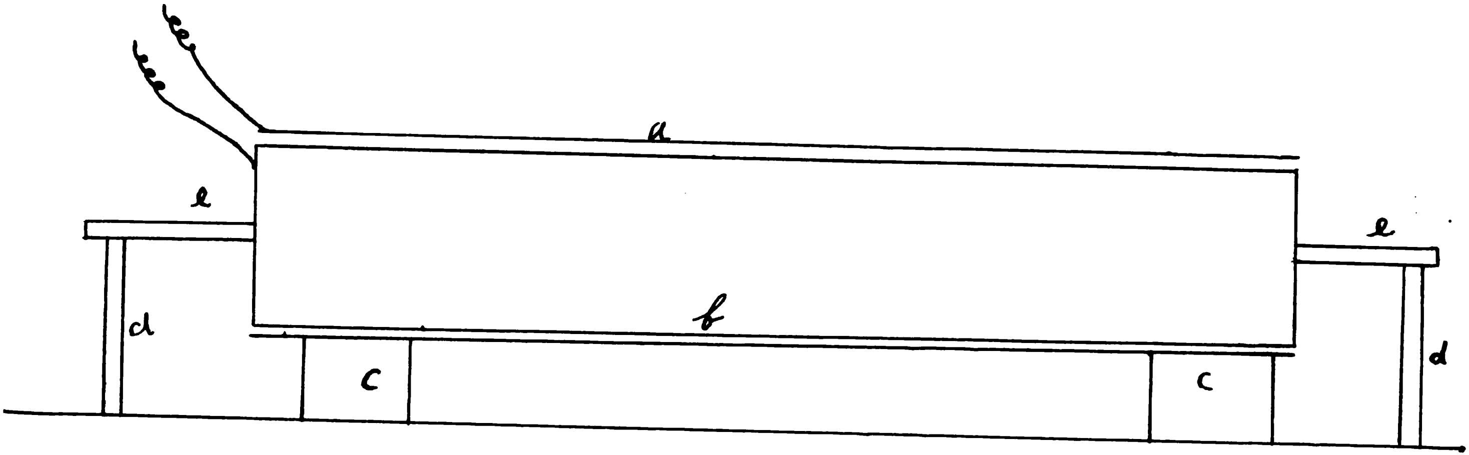


Fig V

EXPLANATION OF DIAGRAMS.

Fig. I. Diagram of complete set up (second set of experiments)

A. Quadrant Electrometer.
B. Switch, operated by string.
C. Rods with grounded casings, used for electrometer connections.
D. Air tight box containing electrodes.
E..Pressure gage.
F. 85 volt battery.
S. Wash bottle containing sulphuric acid.
m. Wash bottle containing Phosphorus pent-oxide.
n. U tube containing glass wool.

Fig. II. Working parts of second set up.

A. Electrometer.
B. Switch.
C. Air tight box with electrodes.
D. Battery.
E. Earth connection.

Fig. III. Sketch of box with electrodes.

A. Brass bar with 1.2 sq. cm. end area.
B..Same.
C. Ambear bar with groove on which brass bars are rested and notch to lengthen the effective insulating distance between the bars.

D. Amber plugs.

Fig. IV. Glass bell jar containing electrodes used in first set up.

A. Brass bar, end area 1.2 sq. cm.

B. Same.

C. Paraffin support.

D. Same.

Fig. V. Standard condenser used to measure capacity.

a. Brass tube, connected with earth.

b. Smaller brass tube; connected to electrometer system.

c. Sealing wax supports.

d. Same.

e. Brass rod supporting inner tube.

Determination of Sensibility of Electrometer.

First, the capacity of the system was computed as follows. The system was first charged by connecting with a standard cell, so that the potential difference between the quadrants was 1 volt. The cell was then disconnected and the charge divided between the system and a standard condenser. If C be the capacity of the system, C_s that of the standard condenser, d the deflection for 1 volt, d_1 the difflection when the charge was divided and V the potential in the latter case, then:

$$\frac{C}{C + C_s} = \frac{V}{1} = \frac{d_1}{d},$$

or,

$$C = \frac{d_1}{d - d_1} \cdot C_s .$$

Now to measure the current sensibility of the electrometer:

Let q = no. of coulombs received by the electrometer system in one second, C = capacity in microfarads, and v = rise of potential in volts per sec. Then:

$$q = \frac{C}{10^6} \cdot v.$$

But $i = q$ (since current in amperes = coulombs per second).

$\therefore$

$$i = \frac{c \cdot v}{10^6} = \frac{c}{10^6} \cdot \frac{d_1}{d}$$

d	d,
mm.	mm.
210	72
214	75
222	65
218	69
217	72

C_s = 150 electrostatic units.

$$C = \frac{d}{d - d_1} \cdot C_s$$

$$= 76 \text{ electrostatic units}$$

$$= \frac{76}{9 \cdot 10^5} \text{ microfarads.}$$

Now the suspension of the electrometer needle was changed for a more sensitive one after figuring the capacity. Obviously the capacity was not changed by this operation, though the sensibility was of course increased. Hence in computing the sensibility the capacity as computed above and the new deflection for 1 volt were used.

Deflection for 1 volt (new suspension) = 320 mm.

$$i = \frac{C}{10^6} \cdot \frac{d_1}{d}.$$

Now, if we let i be that current which would cause a change of deflection of 1 mm. per second, $d_1 = 1$ and this formula reduces to

$$i = \frac{C}{10^6} \cdot \frac{1}{d}.$$

$$i = \frac{75.9}{9 \cdot 10^5} \cdot \frac{1}{10^6} \cdot \frac{1}{320} = 2.6 \cdot 10^{-13} \text{ amperes.}$$

$\therefore$ a current of $2.6 \cdot 10^{-13}$ amperes would cause a change of deflection of 1 mm. per second.

Accepted C. E. Mendenhall

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